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# RECENT ADVANCES IN CHARM PHYSICS

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ABSTRACT

New results from charm experiments have led to renewed interest in this physics. The charm sector is now seen as a powerful tool to search for new physics and to advance our understanding of the standard model. We owe much of this progress to the combination of precision vertexing and large data samples collected by recent $e^+e^-$ and fixed target experiments. Sensitivities to $D^0 - \overline{D^0}$ mixing and $CP$ violation are approaching some non-standard model predictions. Recent measurements of charmed particle lifetimes and semileptonic decays have added to our understanding of decay mechanisms and the dynamics of heavy-to-light quark transitions. Many of these provide vital input to QCD models and are an essential ingredient in extracting standard model parameters from other measurements. Studies of charmonium production continue to offer new surprises. A recent measurement from Belle indicates that $\sim 60\%$ of $J/\psi$ events produced in continuum $e^+e^-$ collisions are produced with an additional charm quark pair. Fueled by new data from a host of continuing and future experiments, we can expect significant improvement to the standard model and possibly some new surprises.

## 1 Why Charm Physics?

Until recently charm physics has often been overlooked as a tool to understand the standard model and to search for physics beyond the standard model. The reason for this is that the charm quark is neither heavy nor light enough to apply the approximations that have been successful in modeling the dynamics of bottom and strange particles. Long range effects may spoil perturbative predictions of charm decay rates. Advances in lattice QCD, recent advances in experimental sensitivities, and the promise of dramatic improvements from current and future charm experiments has revived interest in this field.

Measurements of several important standard model parameters are presently limited by theoretical uncertainties of non-perturbative QCD. All decay processes involving hadrons are modified by soft processes. The charm sector provides stringent tests of non-perturbative QCD. Recent advances in lattice QCD calculations have allowed predictions to a few percent accuracy for several "gold-plated" calculations, including many charmed particle masses, decay constants, semileptonic form factors [1]. Accurate measurements of these quantities will provide crucial tests of the $\mathcal{O}(1\%)$ uncertainties claimed by lattice QCD.

It is also important to understand the relative importance of different processes which play a role in production and decay of charmed particles. The mechanisms for production of charmonium in $p\overline{p}$ collisions are still not understood. Recent measurements from the $B$ factories have further challenged our understanding of these mechanisms. Measurements of charmed meson and baryon lifetimes provide vital information about the relative importance of different decay processes.

There is potential to observe new physics in the charm sector through searches for $D^0-\overline{D^0}$ mixing and $CP$ violation. Until recent advances in sensitivity, limits on $D^0-\overline{D^0}$ mixing and $CP$ violation in many modes were too large to be of interest. New measurements have enabled the search for new physics to extend into previously inaccessible corners. For example, $D^0-\overline{D^0}$ mixing would be sensitive to down-type non-standard model particles, which may appear in the box diagram for mixing. Such particles would not be observable through $B^0-\overline{B^0}$ and $K^0-\overline{K^0}$ mixing, which are only sensitive to up-type particles.

The standard model contributions to $CP$ violation and $D^0-\overline{D^0}$ mixing in charm decays are expected to be quite small. There is uncertainty in the magnitude of enhancements due to long-distance effects, but these are believed to be well below the present experimental sensitivities. Furthermore, experimental measurements may shed light on the magnitude of these long-distance effects.

There are several important topics not covered in this summary due to time and space constraints such as rare and forbidden decays, charmonium and charmed baryon spectroscopy, measurement of the $D^{*+}$ width, and tests of $CPT$ invariance, to name a few. The use of Dalitz analyses of multi-body charm meson decays and radiative $J/\psi$ decays to study light meson/glueball/exotic spectroscopy is covered in other talks from this conference by Brian Meadows and Shen Xiaoyan.

## 2 Searches for New Physics Using D Meson Decays

### 2.1 $D^0 - \overline{D^0}$ Mixing

$D^0 - \overline{D^0}$ mixing is described by amplitudes $x \equiv \Delta M/\Gamma_D$ and $y \equiv \Delta\Gamma/2\Gamma_D$, where $x$ and $y$ arise from differences in the masses ($\Delta M$) and widths ($\Delta\Gamma$), respectively, of the mass eigenstates of the $D^0$ meson, where $\Gamma_D$ is the observed width of the $D^0$ meson. The standard model predictions for $x$ and $y$ are below $10^{-3}$. The amplitude $x$ could be further suppressed by the GIM[2] mechanism, however both $x$ and $y$ could be enhanced by long-distance contributions. New physics could lead to an enhancement of $x$, but is not expected to contribute to the amplitude $y$.

One searches for $D^0 - \overline{D^0}$ mixing by studying the "wrong-signed" (WS) final state of $D^0$ meson decays, such as $D^0 \to K^+\pi^-$ [3]. Contributions to the WS signal may come from the $D^0$ mixing into a $\overline{D^0}$ followed by a Cabibbo-favored (CF) decay or from standard model doubly Cabibbo-suppressed (DCS) decays with amplitude $R_D$ in the case of hadronic final states. The "right-signed" (RS) decays come from Cabibbo-favored decays, such as $D^0 \to K^-\pi^+$.

In order to extract mixing parameters from hadronic final states, such as $D^0 \to K^+\pi^-$, one must use reconstructed $D^0$ candidate proper time information to distinguish possible contributions from $x$, $y$, and $R_D$. The time dependence of the amplitude contains a pure DCS term, a pure mixing term, and an interference term, each with a distinct proper time distribution:

$$r(t) = \left[R_D + \sqrt{R_D}y't + \frac{1}{4}(x'^2 + y'^2)t^2\right] e^{-t}. \tag{1}$$

The primes on the $x$ and $y$ indicate that there may be a strong phase difference, $\delta_{\rm fs}$, between the DCS and CF decays in decays to hadronic final states, which modifies the values $x$ and $y$ and depends on the final state under consideration. The two are related by a rotation: $x' = x\cos\delta_{\rm fs} + y\sin\delta_{\rm fs}$ and $y' = y\cos\delta_{\rm fs} - x\sin\delta_{\rm fs}$. Since this strong phase difference is difficult to estimate from calculations, it is *essential* that it measured experimentally in order to distinguish $x$ and $y$ [4].

For semileptonic $D^0$ decays there are no DCS contributions ($R_D = 0$) and Eq. 1 simplifies to

$$r(t) = \frac{1}{4}(x'^2 + y'^2)t^2 e^{-t}. \tag{2}$$

Observation of a WS signal in a semileptonic mode would be an indication of mixing, however, due to the absence of the interference term, one cannot distinguish whether this mixing is from $x$ or $y$.

The present limits on $D^0 - \overline{D^0}$ mixing parameters $x$ and $y$ from different measurements are summarized in Fig. 1. The limits from the channel $D^0 \to K^+\pi^-$ are plotted assuming $\delta_{\rm fs} = 0$. If this assumption is not made, all possible rotations of these regions about the origin must be considered, leading to much weaker limits.

### *2.1.1* $D^0 \to K^+\pi^-$

Presently, the best limits on $x'$ come from measurements of $D^0 \to K^+\pi^-$ from the CLEO [5] and FOCUS [6] collaborations. CLEO performs fits with and without the assumption of $CP$ conservation. Both experiments observe WS signals consistent with DCS, but both seem to favor negative values of $y'$. The 95% confidence limits on mixing parameters $x'$ and $y'$ from CLEO, assuming $CP$ conservation, are $|x'| < 2.8\%$ and $-5.2\% < y' < 0.2\%$, respectively. The corresponding limits from FOCUS are $|x'| < 3.9\%$ and $-12.4\% < y' < -0.6\%$.

Both Belle and BaBar have preliminary measurements of the time-integrated WS rate, $R_{WS}$ based on 317 and 210 events respectively, corresponding to WS rates of $R_{WS} = (0.372 \pm 0.025^{+0.009}_{-0.014})\%$[7] and $R_{WS} = (0.383 \pm 0.044 \pm 0.022)\%$ [8, 9]. The combined world average is $R_{WS} = (0.37 \pm 0.02)\%$ [10].

### *2.1.2* $D^0$ *Decays to Multi-body Final States*

CLEO has also measured $R_{WS}$ in multi-body channels $D^0 \to K^+\pi^-\pi^0$ and $D^0 \to K^+\pi^-\pi^+\pi^-$ with results $R_{WS} = (0.43^{+0.11}_{-0.10} \pm 0.07)\%$ and $R_{WS} = (0.41^{+0.12}_{-0.11} \pm 0.04)\%$, respectively [11, 12]. $R_{WS}$ need not be the same for different decay modes, however. With the large data samples from the $B$ factories, it may be possible to set $D^0 - \overline{D^0}$ mixing limits using combined Dalitz plot and proper time fits in multi-body modes. These modes may prove useful in searching for $CP$ violation and understanding strong phase shifts [13].

### *2.1.3* $\delta_{K\pi}$ *from* $D^0 \to K^0\pi^0$

Measurements of $D^0 \to K^+\pi^-$ cannot distinguish between $x$ and $y$ without knowledge of the strong phase shift $\delta_{K\pi}$ between the CF and DCS decays. Furthermore,

if $y$ turns out to be large, then it will not be possible to extract precise limits on $x$ without knowledge of $\delta_{K\pi}$. While the theoretical bias is toward a small phase, this quantity must be measured in order to distinguish between new physics and $y$-type standard model mixing. The strong phase $\delta_{K\pi}$ can be pinned down by comparing different $D \to K\pi$ decay rates. Belle has measured the asymmetry of the rates of $D^0 \to K_S^0\pi^0$ and the previously unmeasured $D^0 \to K_L^0\pi^0$ [14, 15]. Their preliminary measurement is not yet sensitive enough to provide a measurement of $\delta_{K\pi}$

$$A = \frac{\Gamma(D^0 \to K_S^0\pi^0) - \Gamma(D^0 \to K_L^0\pi^0)}{\Gamma(D^0 \to K_S^0\pi^0) + \Gamma(D^0 \to K_L^0\pi^0)} = 0.06 \pm 0.05 \pm 0.05, \tag{3}$$

however, improvements are expected as more data comes in.

#### *2.1.4* $D^0 \to K_S^0\pi^+\pi^-$

The decay $D^0 \to K_S^0\pi^+\pi^-$ may be used to measure $x$ and $y$ directly since the strong phase difference may be extracted simultaneously in a time-dependent fit to the Dalitz plot. This is possible because both the RS and WS decays in the submode $D^0 \to K^{*\pm}\pi^{\mp}$ have the same final state. Thus, one can fit for the phase difference directly. The sign of $x$ can also be extracted from such a fit.

CLEO has presented evidence for a WS amplitude and has measured the branching fraction relative to the RS mode to be

$$\frac{\mathcal{B}(D^0 \to K^{*+}\pi^-)}{\mathcal{B}(D^0 \to K^{*-}\pi^+)} = (0.5 \pm 0.2 \ {}^{+0.5}_{-0.1} \ {}^{+0.4}_{-0.1})\% \tag{4}$$

and the strong phase difference between the RS and WS to be $(189^\circ \pm 10 \pm 3^{+15}_{-5})^\circ$ using a time-independent Dalitz plot fit [16]. The last uncertainty is due to the choice of resonances and model. No $CP$ violating effects were observed when separating the sample into $D^0$ and $\overline{D^0}$ subsamples. Results of a time-dependent fit with limits on $x$, $y$, and $CP$ violation are expected soon. This channel may offer the greatest sensitivity to $x$ at the large integrated luminosities already collected by Belle and BaBar.

#### *2.1.5 Measurement of $y_{CP}$ Using $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$*

The decays of the $D^0$ to $CP$ eigenstates may be used to measure the amplitude

$$y = \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_{CP+} - \Gamma_{CP-}}{\Gamma_{CP+} + \Gamma_{CP-}}. \tag{5}$$

Decays to the $CP$-even final states $K^+K^-$ and $\pi^+\pi^-$ are the most accessible experimentally and have been studied by BaBar [17], Belle [18], CLEO [19], E791 [20], and

FOCUS [21]. The value of $y$ is extracted by assuming $CP$ conservation and comparing with the well-measured lifetime of the non-$CP$ $D^0 \to K^-\pi^+$ decay mode:

$$y_{CP} = \frac{\tau_{K^-\pi^+}}{\tau_{K^+K^-}} - 1. \tag{6}$$

Many systematic uncertainties cancel in this ratio.

The present world average of $(1.0 \pm 0.7)\%$ [10] is dominated by recent measurements from the BaBar, Belle, and FOCUS experiments of $(1.4 \pm 1.0^{+0.6}_{-0.7})\%$ [17], $(-0.5 \pm 1.0 \pm 0.8)\%$ [18], and $(3.4 \pm 1.4 \pm 0.7)\%$ [21], respectively.

#### 2.1.6 *Semileptonic Channels*

As shown in Eq. (2), a signal for WS semileptonic $D^0$ decay would be evidence for $x$- or $y$-type $D^0 - \overline{D^0}$ mixing. No signal has been observed and upper limits have been set. The most recent limits on $R_{mix} \equiv 1/2(x^2 + y^2)$ using semileptonic WS decays are from E791 ($< 0.5\%$ @ 90%C.L.) [22] and CLEO ($< 0.87\%$ @ 95%C.L.) [23], measured in the channels $D^0 \to K^+\mu^-\overline{\nu_\mu}$ and $D^0 \to K^{*+}e^-\overline{\nu_e}$, respectively. When comparing, note that the E791 measurement is quoted as a 90% C.L. limit. FOCUS has presented an *estimated* sensitivity of $< 0.12\%$ @ 95%C.L. (with statistical errors only) in the channel $D^0 \to K^+\mu^-\overline{\nu_\mu}$ [24] but has not yet presented an actual result.

### 2.2 $CP$ Violation

$CP$ violation may manifest itself in three possible ways: 1) as a difference in the decay rates for charge conjugate states ($D \to f \neq \overline{D} \to \overline{f}$), 2) as an asymmetry in the mixing rate for charge conjugate states ($D^0 \to \overline{D^0} \neq \overline{D^0} \to D^0$), or 3) as a difference in the phase of interference between mixing and decay contributions for charge conjugate states.

Two ingredients are required in order to observe non-standard model physics through $CP$ violation. First, the decay amplitude must have contributions from at least two diagrams with different weak phases. Second, there must be a non-negligible strong phase shift between two of the processes. The strong phase shift is expected to be non-zero in charm decays, since $SU(3)$ flavor symmetry is known to be badly violated in some decays. For example, the ratio of rates $BR(D^0 \to K^+K^-)/BR(D^0 \to \pi^+\pi^-)$ is approximately three times larger than the value of one predicted under the assumption of $SU(3)$ flavor symmetry.

Since $CP$ violation is expected to be zero for doubly Cabibbo-suppressed and Cabibbo-favored decays within the standard model this is a good place to look

for new physics. Many doubly Cabibbo-suppressed modes were observed only recently and are being studied for the first time. CLEO has measured $CP$ asymmetries in decay, mixing, and interference in the doubly Cabibbo-suppressed channel $D^0 \to K^+\pi^-$ to be consistent with zero: $A_{\mathrm{decay}} = (-1^{+16}_{-17} \pm 1)\%$, $A_{\mathrm{mixing}} = (23^{+63}_{-80} \pm 1)\%$, $\sin\theta = (0 \pm 60 \pm 1)\%$ [5].

For singly Cabibbo-suppressed decays, the standard model prediction is of order $10^{-3}$ or below, and arises out of the interference between tree and penguin amplitudes. Asymmetries in several modes have been measured recently by CLEO [25], FOCUS [21], and E791 [20], including $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$, $D^0 \to K^+K^-\pi^+$ channels, which are now measured to be $(0.48\pm1.57)\%$, $(2.1\pm2.6)\%$, and $(0.2\pm1.1)\%$, respectively [10].

Several other decay channels have also been studied and are not covered in this paper. We can look forward to $CP$ violation searches utilizing not only comparisons of rates, but also the detailed amplitude and phase observables from Dalitz plot analyses of multi-body modes.

## 3 Measurements Which Provide Input to QCD Models

### 3.1 Charm Semileptonic Decays

Our understanding of many important standard model parameters, such as the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements $|V_{ub}|$ and $|V_{cb}|$ are limited by theoretical uncertainties in the QCD of heavy quark semileptonic decays. Many of these uncertainties in $B$ meson decays can be reduced using lattice QCD with input from analogous charm decays, such as $D^+ \to \overline{K^{*0}}\ell^+\nu_\ell$, $D^0 \to \pi\ell\nu_\ell$, $\rho\ell\nu_\ell$, $K\ell\nu_\ell$ or $D_s^+ \to \phi\ell\nu_\ell$.

The normalized branching fraction of the decay $D^+ \to \overline{K^{*0}}\ell^+\nu_\ell$

$$R_\ell^+ \equiv \frac{\Gamma(D^+ \to \overline{K^{*0}}\ell^+\nu_\ell)}{\Gamma(D^+ \to \overline{K^-}\pi^+\pi^+)} \tag{7}$$

has been measured most recently by the FOCUS ($R_\mu^+ = 0.602 \pm 0.010 \pm 0.021$) [26], CLEO ($R_e^+ : 0.74 \pm 0.04 \pm 0.05$, $R_\mu^+ : 0.756 \pm 0.105 \pm 0.06$)) [27], E687 ($R_\mu^+ = 0.588 \pm 0.042 \pm 0.063$) [31], and E691 ($R_e^+ = 0.49 \pm 0.04 \pm 0.05$) [31] experiments. FOCUS observed dramatic interference effects in this decay, which result in a large asymmetry in the $\overline{K^*}$ decay angle for masses below the $\overline{K^*}$ pole mass and almost no asymmetry for masses above the pole [26]. They find this to be consistent with a small, but significant even-spin contribution to the $K\pi$ final state. They also measure the semileptonic form factor ratios $r_v$ and $r_2$ including the $S$-wave component to be $1.504 \pm 0.057 \pm 0.039$ and $0.875 \pm 0.049 \pm 0.064$, respectively.

FOCUS also has a preliminary measurement of $D_s^+ \to \phi\mu^+\nu_{mu}$ with a branching fraction of $0.54 \pm 0.033 \pm 0.048$ [24].

### 3.2 Charmed Meson and Baryon Lifetimes

Measurements of charmed baryon and meson lifetimes provide important insight into the decay processes of heavy mesons and baryons. Depending on the particular decay, different processes such as external spectator, internal spectator, $W$ exchange, or annihilation may be important. Interference effects may have a large role in determining the observed lifetime. Comparisons of non-perturbative QCD models with the measured lifetime hierarchy of charmed particles provide an important test of these models.

The striking difference in the observed $D^0$ and $D^+$ lifetimes is now understood to be due to interference between diagrams contributing to $D^+$ decays, but not those contributing to $D^0$ decays. The $D^0$ and $D^+$ lifetimes are now measured to a fraction of a percent, $410.4 \pm 1.5$ fs [10, 28, 20, 29, 30, 31] and $1042.7 \pm 6.9$ fs [10, 28, 30, 31], respectively, and the $D_s^+$ lifetime is measured to about two percent, $490.7 \pm 8.4$ fs [10, 32, 31]. The $\tau_{D^0}$ and $\tau_{D^+}$ averages are dominated by recent measurements from the FOCUS collaboration [28, 31] of $409.6 \pm 1.1 \pm 1.5$ fs and $1039.4 \pm 4.3 \pm 7.0$ fs, respectively. A preliminary measurement of the $D_s^+$ lifetime from FOCUS of $506 \pm 8$ fs using half of their data sample was not included in the average, since the systematic uncertainty was not yet known.

Lifetimes of the $\Lambda_c^+$, $\Xi_c^+$, and $\Xi_c^0$, charmed baryons have been measured recently by the fixed target experiments FOCUS [33], SELEX [29], and E687[31] and by the CLEO $e^+e^-$ experiment [34]. Most of the charmed baryon lifetime hierarchy is described quite well by the theory. One notable exception is the ratio of the lifetimes of $\Xi_c^+$ and $\Lambda_c^+$, for which the measurement is approximately a factor of two larger than the prediction. New and more precise measurements of charmed hadron lifetimes and decay modes will provide important guidance to our understanding of heavy hadron decays.

### 3.3 Charmonium Production Mechanisms

Measurements of charmonium production have provided many surprises and many challenges to our conception of how such particles are produced. During Run I of the Tevatron, the production cross sections for charmonium and bottomonium states exceeded NRQCD predictions by as much as two orders of magnitude [35, 36]. Many new contributing processes were proposed, including new fragmentation

contributions and production in a color-octet state [37].

Recently, the Belle and BaBar collaborations have made measurements which test NRQCD using $e^+e^-$ collisions below the $\Upsilon(4S)$. At these energies, the following processes are expected to contribute:

$$
\begin{array}{rccr}
e^+e^- \to J/\psi gg & \text{Singlet, octet} & \text{dominant} & (8)\\
e^+e^- \to J/\psi g & \text{Octet} & \text{dominant at endpoint} & (9)\\
e^+e^- \to J/\psi c\bar{c} & \text{Octet, singlet} & \text{Four charm gluon splitting} -- \mathcal{O}(10\%) & (10)\\
e^+e^- \to J/\psi q\bar{q} & \text{Octet} & \text{Two charm gluon splitting} -- \text{Small} & (11)
\end{array}
$$

Both the BaBar and Belle collaborations have observed $J/\psi$ production in the continuum below the $\Upsilon(4S)$ resonance. One may test for the color-octet contribution of Eq. (9) predicted by NRQCD by examining the momentum $p^*$ and polar angle ($\theta^*$) of the $J/\psi$ in the center-of-mass frame. The angular $\cos\theta^*$ distribution may be fit to $1 + A \cdot \cos^2\theta^*$ in low and high $p^*$ bins in order to test the models. NRQCD and color singlet models both predict a flat ($A = 0$) distribution at low $p^*$. At high momentum the color singlet model predicts $A \sim -0.8$ while NRQCD predicts $0.6 < A < 1.0$. BaBar has performed these fits for $p^* < 3.5$ GeV/$c$ and $p^* > 3.5$ GeV/$c$ and find $A = 0.05 \pm 0.22$ and $A = 1.5 \pm 0.6$, respectively [38], which is consistent with NRQCD. The same measurement from Belle [39] yields a large positive value $A = 0.9 \pm 0.2$ at all momenta. This distribution is only expected for the color singlet four-charm gluon splitting of Eq. (10), which is predicted to be small. In some models, the leading color-octet mechanism of Eq. (9) is expected to contribute only in the high $p^*$ end-point region, where it would give $A \sim +1$. No excess was observed in the high $p^*$ region in either measurement.

Belle recently presented a surprising result indicating that four-charm production (Eq. (10)) comprises the *majority* of continuum $J/\psi$ production [15]. They studied the spectra of mass recoiling against the $J/\psi$ and observe a clear threshold at twice the charm mass and evidence for peaks at the $\eta_c$, $\chi_{c0}$, and $\eta_c'$ masses. They also search for a third associated charm quark through the decays $e^+e^- \to J/\psi D^* X$ and $e^+e^- \to J/\psi D^0 X$. They observe signals of 5.3 and 3.7 standard deviations statistical significance. Using the JETSET fragmentation rates they convert these rates into a cross section for $e^+e^- \to J/\psi c\bar{c}$. They find that four-charm production accounts for approximately 60% of continuum $J/\psi$ production:

$$
\frac{\sigma(e^+e^- \to J/\psi c\bar{c})}{\sigma(e^+e^- \to J/\psi X)} = 0.59^{+0.15}_{-0.13} \pm 0.12. \qquad (12)
$$

This is quite a surprise considering that the prediction is of order 10%. As more data comes in from both experiments, our understanding of these production mechanisms should become more clear.

## 4 The Future of Charm Physics

FOCUS, CLEO, and E791 continue to produce important results using their well-developed analysis tools and final data samples. Many of the most challenging analyses involving Dalitz plot and proper time fits are now bearing physics results.

The B factory experiments Belle and BaBar are expected to add approximately a factor of ten to their already large data samples over the next few years. Many of the first round of analyses from these experiments are close to bearing results with a factor of 5-10 times the CLEO statistics.

Dedicated charm experiments CLEO-c/CESR-c and BES III are proposed for 2003 and 2005/6, respectively. A funding decision will be made soon regarding the CLEO-c/CESR-c proposal. CLEO-c will allow precision measurement of the decay constants $f_D$ and $f_{D_s}$ to a precision of 2.3% and 1.7%, respectively, using a sample of approximately 30 million events (six million *tagged* $D$ decays)– 310 times the Mark III data sample. Precise measurements of several important absolute branching fractions, semileptonic form factors will be made, as well as high statistics searches for $D^0 - \overline{D^0}$ mixing, $CP$ violation, and rare $D$ decays.

CDF has demonstrated the ability to trigger on charm decays in the messy environment of $p\overline{p}$ collisions using its silicon trigger. DØ is planning to implement a silicon vertex trigger during Run II of the Tevatron. These experiments benefit from a large charm cross section which is approximately a factor of ten larger than the bottom cross section. Extrapolating from the preliminary CDF results [40] and assuming that the trigger rates are sustainable at higher luminosities, one can expect approximately $10^7$ $D^0 \rightarrow K^-\pi^+$ events. Assuming the same efficiency ratio for WS, one expects approximately 15,000 WS $D^0 \rightarrow K^+\pi^-$ events and a $CP$ violation reach of perhaps $10^{-3}$.

Toward the end of this decade, the proposed BTeV and LHCb experiments are expected to take data. The BTeV trigger will require only two tracks with a detached vertex and will have a large acceptance for charm. The LHCb trigger is not expected to have significant acceptance for charm. Using very crude estimates and many assumptions, one expects approximately $10^8$ RS $D^0 \rightarrow K^-\pi^+$ events and approximately 150,000 WS $D^0 \rightarrow K^+\pi^-$ events to be collected by BTeV. Such samples would allow a $CP$ violation reach down to $\sim 10^{-4}$.

## 5 Summary

Charm physics has proved to be an important tool for understanding the standard model and searching for new physics. Recent searches for new physics are starting to exclude some non-standard model predictions. Lattice QCD awaits validation of its predictions of form factors, rates, and decay constants of charm decays. These measurements effect the determination of other important quantities, such as $|V_{ub}|$ and $|V_{cb}|$. Similarly, studies of charmed hadron lifetimes feed back into our understanding of decay processes. Finally, measurements of charmonium production, both at hadron and $e^+e^-$ colliders continue to offer new surprises and challenges to NRQCD. The interest in charm physics will continue to grow as the $\Upsilon(4S)$, charm factories, and hadron experiments weigh in with new and more precise measurements.

## References


1. G. P. Lepage, High Precision Nonperturbative QCD, Presentation at Hadron Physics 2002, April 2002, Bento Goncalves, Brazil.

2. S. L. Glashow, J. Iliopolous, and L. Maiani, Phys. Red. D **2**, 1285 (1970).

3. Charge conjugate modes are implied throughout this paper except where explicitly noted.

4. A. F. Falk, Y. Nir, A. A. Petrov, JHEP 9912 (1999) 019.

5. R. Godang *et al.*, Phys. Rev. Lett. **84**, 5038 (2000).

6. J. M. Link *et al.*, Phys. Rev. Lett. **86**, 2955 (2001); J. M. Link, Recent Results in Charm Mesons, Presentation at The Fifth KEK Topical Conference– Frontiers in Flavor Physics, November, 2001, Tsukuba, Japan.

7. K. Abe, *et al.*, "A Measurement of the Rate of Wrong-sign Decays $D^0 \to K^+\pi^-$", Proceedings of The 31st International Conference on High Energy Physics, Amsterdam, July 2002, hep-ex/0208051.

8. U. Egede, "Determination of the Wrong Sign Decay Rate $D^0 \to K^+\pi^-$ and the Sensitivity to $D^0 - \overline{D^0}$ Mixing", Proceedings of the International Europhysics Conference on HEP, Budapest, July, 2001, hep-ex/0111062.

9. Unless otherwise noted, the statistical uncertainty is quoted first and the systematic is quoted second. For averages, the systematic and statistical uncertainties are added in quadrature.

10. These are my weighted averages including the Particle Data Group measurements and all known published or preliminary measurements up to and including those presented at the ICHEP 2002 conference. Averages were calculated using the technique summarized in the Review of Particle Physics.

11. G. Brandenburg *et al.*, Phys. Rev. Lett. **87**, 071802 (2001).

12. S. A. Dytman *et al.*, Phys. Rev. D **64**, 111101 (2001).

13. C. Chiang, J. L. Rosner, Phys. Rev. D **65**, 054007 (2002).

14. K. Abe *et al.*, "Measurement of $D^0$ decays to $K_L^0\pi^0$ and $K_S^0\pi^0$ at Belle", XX International Symposium on Lepton and Photon Interactions at High Energies, Rome, July 2001, hep-ex/0107078.

15. B. Yabsley, "Current Charm Studies at Belle", presented at the Meeting of the Division of Particles and Fields, Williamsburg, May 2002.

16. H. Muramatsu, *et al.*, submitted to Phys. Rev. Lett., hep-ex/0207067.

17. A. Pompili, "Charm Mixing and Lifetimes at BaBar", XXXVII Rencontres de Moriond on Electroweak Interactions and Unified Theories, Les Arcs, March 2002, hep-ex/0205071.

18. K. Abe *et al.*, Phys. Rev. Lett. **88**, 162001 (2002).

19. S. E. Csorna *et al.*, Phys. Rev. D **65**, 092001 (2002).

20. E. M. Aitala *et al.*, Phys. Rev. Lett. **83**, 32 (1999).

21. J. M. Link *et al*, Phys. Lett. B **485**, 62 (2000).

22. E. M. Aitala *et al*, Phys. Rev. Lett. **77**, 2384 (1996)

23. A. Smith, "Recent Charm Results from CLEO", presented at XXXVIIth Recontres de Moriond QCD, Les Arces, March 2002.

24. S. Malvezzi, "Charmed Mesons Lifetimes, Decays, Mixing and CPV Results from FOCUS", 31st International Conference on High Energy Physics, Amsterdam, July 2002.

25. S. E. Csorna *et al.*, Phys. Rev. D **65**, 092001 (2002).

26. J. M. Link *et al*, Phys. Lett. B **541**, 243 (2002); J. M. Link *et al.*, Phys. Lett. B **535**, 43 (2002); J. M. Link *et al.*, hep-ex/0207049 (2002);

27. G. Brandenburg *et al.*, Submitted to Phys. Rev. Lett., hep-ex/0203030.

28. J. M. Link *et al.*, Phys. Lett. B **537**, 192 (2002).

29. A. Kushnirenko *et al.*, Phys. Rev. Lett. **86**, 5243 (2001).

30. G. Bonvicini *et al*, Phys. Rev. Lett. **82**, 4586 (1999).

31. D. E. Groom *et. al*, Eur. Phys. J. **15**, 1 (2000).

32. M. Iori *et al.*, Phys. Lett. B **523**, 22 (2001).

33. J. M. Link *et al.*, Phys. Lett. B **523**, 53 (2001); J. M. Link *et al.*, Phys. Lett. B **541**, 211 (2002); J. M. Link *et al.*, Phys. Rev. Lett. **88**, 161801 (2002).

34. A. H. Mahmood *et al*, Phys. Rev. Lett. **86**, 2232 (2001); A. H. Mahmood *et al*, Phys. Rev. D **65**, 031102, (2002).

35. S. Abachi *et al.*, Phys. Rev. Lett **74**, 2632 (1995).

36. F. Abe *et al.*, Phys. Rev. Lett **74**, 2626 (1995).

37. E. Braaten, S. Fleming, T.C. Yuan, Ann. Rev. Nucl. Part. Sci. **46**, 197 (1996).

38. B. Aubert *et al.*, Phys. Rev. Lett. **87**, 162002 (2001).

39. K. Abe *et al.*, Phys. Rev. Lett. **88**, 052001 (2002).

40. S. Donati, "First Run II Results from CDF", XXXVIIth Rencontres de Moriond, Les Arces, March 2002; D. Kaplan, "Hadron Collider Charm Physics Reach", presented at the Meeting of the Division of Particles and Fields, Williamsburg, May 2002.

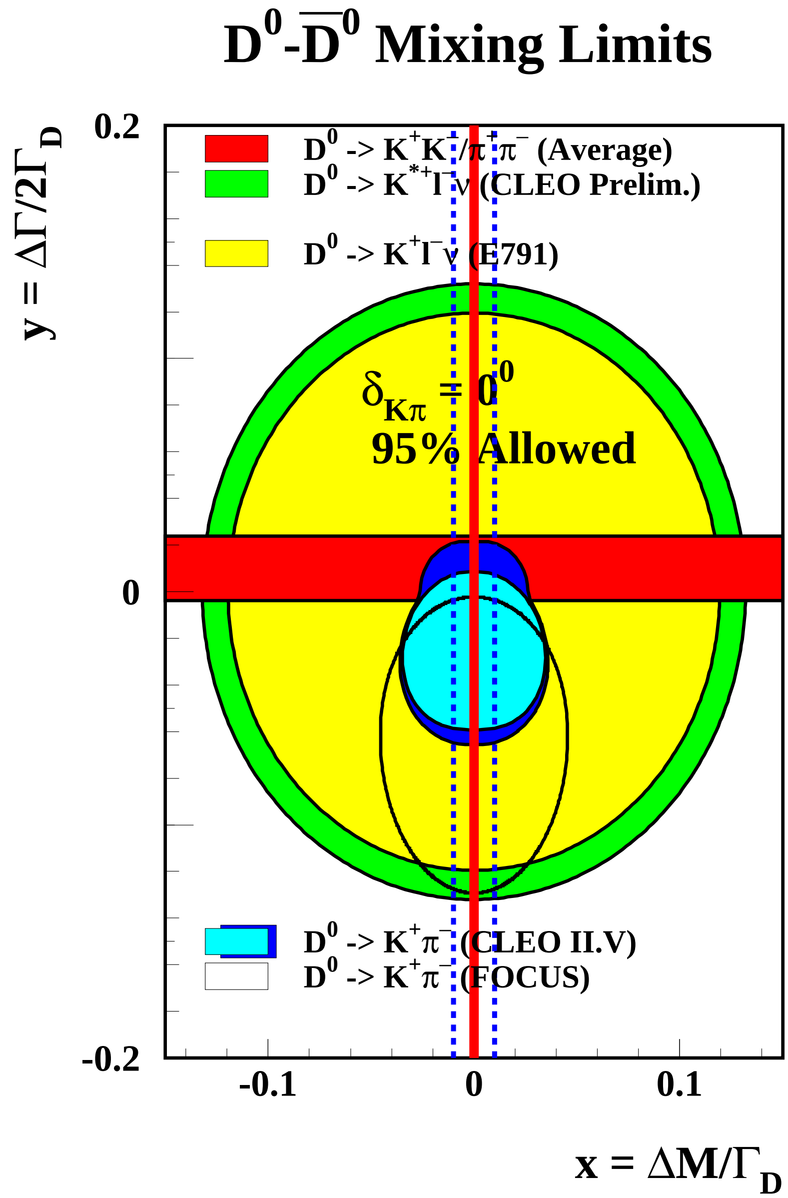


Figure 1: Our present knowledge of $D^0-\overline{D^0}$ mixing. The solid vertical lines indicate a "typical" standard model prediction for $x$. The dashed vertical lines indicate the upper range of non-standard model predictions for $x$. The strong phase shift $\delta_{\rm fs}$ between the Cabibbo-favored and DCS decays is assumed to be zero in plotting the $D^0 \to K^+\pi^-$ results. While the strong phase shift is expected to be close to zero, until it is actually measured, the allowed region from the $D^0 \to K^+\pi^-$ measurements must be expanded to include the area swept out by rotating these regions about the origin.